Design, Optimization, and Modelling Issues of Net-Zero Energy Solar Buildings

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Abstract

The design of net-zero energy solar buildings (NZESBs) presents a challenge because there is no established design strategy to systematically reach this goal and many of the available building energy tools have limited applicability for such advanced buildings. This paper reviews current design practice and tools for designing NZESBs through a literature review and a survey. It also discusses modelling issues and presents the procedure used in several redesign and optimization case studies of existing NZESBs that Subtask B (STB) of the IEA SHC Task 40/ECBCS Annex 52 project "Towards Net Zero Energy Solar Buildings" is performing. The case studies will identify gaps in existing tools and help develop strategies for the use of design tools in establishing near optimal NZESB designs.

1 Introduction

Net-zero energy solar buildings (NZESBs) are emerging as a quantifiable design concept and promising solution to minimizing the environmental impact of buildings. These buildings, which minimize energy consumption and optimally use incident solar radiation, both passively and actively, are usually defined as those which export as much energy as they import, over the course of a year (also known as net-zero site energy [1]). The issues of modelling, design and optimization of such buildings are being addressed by Subtask B (STB) of the IEA SHC Task 40/ECBCS Annex 52 (henceforth "the Task") [2]. Despite growing awareness of NZESBs, this team of researchers has identified many gaps in the systematic design and optimization of such buildings, both in terms of process and analysis tools, through a survey and literature review. For instance, the following questions must be considered:

- What is the appropriate model resolution (e.g., detail and accuracy) for each major stage of the design of NZESBs?
- What is the role of simple spreadsheet-based tools (e.g., RETScreen and PHPP [3]) versus more advanced detailed simulation (e.g., ESP-r and EnergyPlus [4]) and optimization tools?

- What other tool capabilities are needed model new technologies for NZESBs such as building fabric-integrated thermal storage (e.g. phase-change materials (PCMs))?

A 3-dimensional conceptual problem space has been developed (Figure 1) to represent the conceptual framework being used by STB to define the role of computer modelling in NZESB design. Different software packages include different technologies and simulate building fabric energy transfer with different levels of detail. They also utilize different techniques to model the transient response of buildings and their systems to changes in internal and external thermal loads. This paper presents the initial major findings of STB, including the key results of a survey, the benchmark methodology, a discussion of modelling resolution and the design process, and finally, the case study methodology.

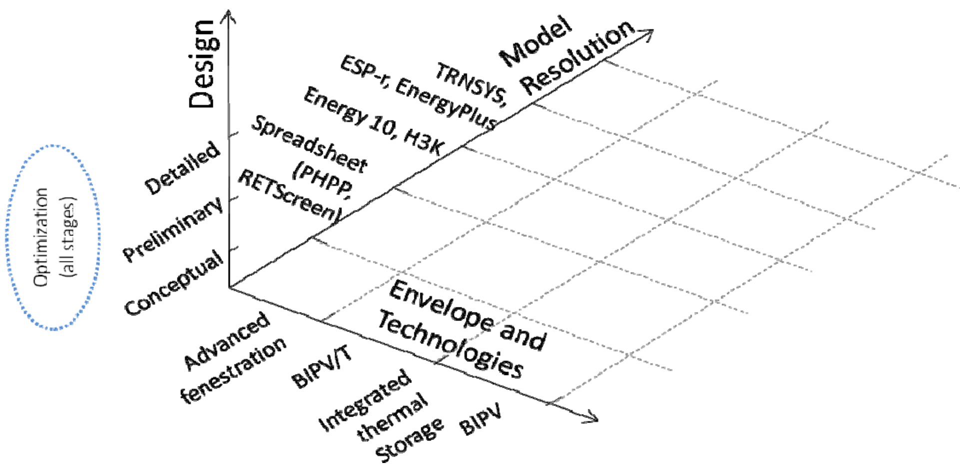

Figure 1: The 3D matrix representing model resolution, technologies, and design stage

2 Literature Review and Survey Results

Several extensive works have been written about both building energy design/simulation tools [5 & 6] and low-energy building design processes [7-10]. However, the focus has been largely on conventional or low-energy buildings. The purpose of this work is to identify unique aspects of NZESBs, which combine energy efficiency measures and passive solar design with on-site renewable energy generation to achieve a net-zero energy balance over an average year. The survey was aimed at determining how NZESBs are currently being designed.

2.1 Survey Results

In order to establish an understanding of how design tools are currently being applied to the design of NZESBs, a survey was conducted within the Task. The objective was to determine which and how many tools are being used and to determine gaps of current tools or of the design process. In all, 32 national experts from the Task responded, including both researchers and designers. The key results of the 29-question survey are outlined in Tables 1 through 4.

Table 1: Typically, at which stage of the building design process do you first create an energy model?

Conceptual/early stage design	59%
After the design is complete, but opportunities remain for improvement	34%
After the design has been finalized	6 %

This indicates that early stage simulation is more prevalent in NZEBSs than other buildings because of the aggressive performance goals that are established.

Table 2: Name NZESB design tool features that are lacking.

Technical features	**Other features**
• Building-integrated solar technologies • Phase-change materials • Adiabatic cooling • Thermal bridges • Coupling of thermal and daylighting performance for double facades	• User-friendliness for integration of renewables. • Optimization • GUI for HVAC in EnergyPlus • Should identify key parameters and opportunities for decoupled models • Solar potential analysis • Simple models for complex integrated systems (e.g., SDHW with GSHP)

Table 3: Brainstorm features for future development

• Faster feedback • Guidance towards better designs • Design evolution • Facility for batch runs with optimization • Direct calculation of primary energy, emissions, and costs. • Design day output • Better user interface with more examples • Better contextual help for each feature • Sensitivity analysis for each input	• Explanation of limitations of each model • Include parameters such as: thermal admittance, time constants • Faster feedback, at cost of accuracy, since we mainly care about relative performance • Offer method for managing multiple designs • Better post-processing (e.g., export to Excel)	• Include electricity demands of different plug loads. • Explanation of limitations of model • Flags for inappropriate inputs • Cost data/input • Financial analysis • Better interoperability between tools • Rules of thumb built in • Simplify them to allow architects to use them

3 Benchmark

Following the survey findings, qualitative and quantitative benchmark protocols were established to compare the building energy simulation tools commonly used during the design of NZESB by assessing their capabilities and accuracy. These benchmarks aim at informing tool developers of gaps and needs of NZESB modelling, one of the goals of STB.

In the qualitative benchmark, tool capabilities and target outputs required for the design of NZESBs were identified based on six case studies (listed in Section 7). For each building, the features implemented to achieve net-zero energy were identified as well as the economic, environmental and energy target outputs required during their design. Using the collected information, matrices of target values and tool requirements specifically related to the needs of NZESB modelling were developed. These matrices were then used to qualitatively evaluate the modelling capabilities of the following software programs, listed in order from lowest to highest modelling resolution (see Section 4 for details on resolution): RETScreen and PHPP, HOT3000, TRNSYS and EnergyPlus (Figure 1). The key outputs resulting from the qualitative benchmark analysis are as follows:

For the six buildings considered, more than 25 different active and passive technologies for reducing net energy consumption were identified.

The recurring characteristics in NZESB design features that can be implemented in all types of tools include high performance building envelope, energy-efficient lighting fixtures and appliances, as well as passive solar design features such as an appropriate aspect ratio, orientation, window area as a fraction of facade/floor area, and shading devices.

Simple tools show some limitation for the following common NZESB design characteristics: daylighting, natural ventilation, passive cooling and the ability to specify the location of thermal mass – a key component of passive solar buildings. One of the case study buildings uses fuel cells for electrical storage. They all use PV as an on-site electricity generation technology even though wind turbines were also implemented in certain cases. While PV models are available in most tools, wind turbines are less prevalent.

The NZESBs considered all have different heating and cooling systems integrating at least two different technologies. Most tools provide explicit models for commonly used technologies such as solar thermal collectors and geothermal heat pumps, but the capability of modelling innovative technologies or interactions between multiple pieces of equipment is usually inexistent or very limited in simple tools.

Output variables related to energy such as total building energy, fuel and electricity consumption by end-use are available in most tools. There is often a lack of information; however, on thermal comfort, heat loss location, peak demand and on the economic and environmental aspects.

The qualitative benchmark aimed at identifying the gaps and issues of tools in terms of capabilities, but not at determining how well the NZESB characteristics are handled by the different tools. This will be shown in the quantitative benchmark which will compare tools on a precise simulation exercise. Two monitored buildings (one commercial, one residential) with reliable experimental data will be modelled in each of the aforementioned simulation tools, and the performance results will be evaluated and compared to the measured values. This will allow the assessment of the accuracy and suitability of tools with different levels of modelling resolution.

4 Modelling **resolution and technology representation**

The term model resolution employed in the previous sections refers to the mathematical-physical modelling detail used in each stage of the design to represent an energy transfer/conversion process such as dynamic heat transfer in the building envelope and interior; generation of electricity, and potentially useful heat, from photovoltaic panels; heating, ventilation and cooling; and lighting and daylight. This model resolution will generally differ with the various stages of the design to reflect the availability and certainty of design details. The two coupled issues of model resolution and technology representation are discussed below in four major categories: (1) envelope heat transfer and thermal storage, (2) HVAC systems, and (3) Building-integrated solar energy systems.

4.1 Envelope heat transfer and thermal storage

During the conceptual stage of the design, when the major geometric parameters and the form of the building are being selected, there is often not enough information available to perform a detailed dynamic thermal simulation of the building response and possibly no need for it. So, a simplified model such as an admittance model [11 & 12] that captures the essential dynamic thermal characteristics of the building may be sufficient for this stage of the design. The objective of the designer must be to determine the appropriate level of resolution necessary to accurately model performance to decide on basic decisions such as window area/type and thermal mass. Often, early stage design tools are unable to characterize overheating and other passive phenomena. Representation of phase change materials (PCM) integrated into the building interior layers requires special modelling approximations [15].

During the detailed stages of the design two methods are generally used: (1) transfer function-based methods which model the building as a linear system and the dynamic building response is obtained by using time domain or frequency domain transfer functions; (2) finite difference techniques, in which the energy balance equations of the building are discretized in space and time, resulting in algebraic equations that are simultaneously solved for variables such as nodal temperatures and heat flows. The finite difference-based methods are generally more flexible and they allow the modelling of nonlinear processes, such as heat storage in phase change materials or a stratified thermal storage tank.

4.2 HVAC systems

Generally, the HVAC system is designed fully during the final stages of the building design. However, the integration of passive solar systems with the HVAC systems both in the design and operation stages of the building is essential to achieve comfortable conditions while saving energy. However, this is usually overlooked because of the absence of any systematic collaboration for integration of building design between architects and engineers, often ignoring the benefits due to solar gains and natural cooling. It is thus essential to lay the foundations for the selection of an appropriate HVAC system at the conceptual stage of the design.

4.3 Building-integrated solar energy systems (thermal, electric, hybrid, daylighting)

These systems will play a major role in achieving the net-zero energy goals and need to be carefully selected, modelled and sized for an accurate design. At the early stage of the design, a simplified software tool such as RETScreen may provide enough accuracy to size a BIPV or a solar thermal system as it provides monthly estimates of energy generated. However, a building-integrated photovoltaic/thermal system (BIPV/T – a hybrid system) that generates both electricity and heat from the BIPV requires estimation of the heat recovered and how it can potentially be used – to heat ventilation air, to heat water or space heating (directly or through a heat pump). To properly simulate these systems, there is a need for tools characterized by a high integrity representation of the dynamic and connected processes.

5 Parametric analysis and NZESB design decision support

A major objective of the Task is to inform and support decision making in the early stages of NZESB design. In the design of NZESB it is very important to identify the most important design parameters and strategies early in design, in order to develop more efficient alternatives and reach optimized design solutions. Informing decisions of NZESB designs can be achieved with the help of prescriptive guidelines or analysis tools. Therefore, one of the Task's activities is to perform a series of parametric analyses. The parametric analysis aims at setting up basic prescriptive guidelines of NZESB design. In parallel, the tools that provide this feature to inform and support decision making will be analyzed.

The result of the preliminary sensitivity analyses shows that ranking the most influential parameters and strategies of NZESB varies strongly across climates. Therefore, setting up universal strategies for NZESB, which are envelope dominated, is not recommended. The integration of parametric analysis features in existing tools is very weak [5 & 17]. Future versions of tools should incorporate design and decision support features that will facilitate NZESB design. This can be achieved by implementing simple sensitivity analysis models.

6 Analyzing the design process

The identification of key characteristics of the NZESB design process is critical. To analyze and optimize it, the methodology of the Information Delivery Manual (IDM) [18] can be used. Two main components of that method are:

1. The “Process Map” (PM) gives a graphical representation of activities, their sequence and the performing actors or disciplines. It answers the questions: “who”, “what” and “when”; thereby providing an overall view on the course of the design process. For this work, the PM of NZESBs used the Business Process Model Notation (BPMN);
2. The “Exchange Requirements” (ER) describes the information that is exchanged between consecutive activities or sub-processes. It defines the required information at any given point of the design process, distinguishing between “required” and “optional” data. Thus, it provides the foundation for the development and a possible certification of building models and interfaces for data-exchange.

The application of this method to the design process of a NZESB guides the design team into making explicit (1) all the hypotheses used during the conceptual design phase and (2) their possible changes over time according to the evolution of concept. For example, if, at a certain stage of the design process, the design team needs to change some heating strategies to optimise the comfort and the energy performance of the building, probably the comfort model has to be changed. This may be the case if the designer follows the Standard EN 15251 which proposes to optimise the building envelope and passive strategies by minimising adaptive discomfort indexes if active cooling plants are not included, otherwise it requires to minimise Fanger discomfort indexes if active cooling plants are included [23]. The change of the comfort model may have direct implications on energy strategies used to reach sustainable summer comfort of very low energy buildings.

The presence of a PM and of ERs for consecutive activities could be very useful to detect the sub-processes that are affected by changes, professionals to be informed about them, and documents that need to be updated

The overall design process of a NZESB can be divided in 4 sub-processes (Figure 2). Each depicted sub-process frame links to a detailed sub-process map. An overall design process map of NZESBs that serves as a guide for future design teams do not need a high detail level. If, on the other hand, the PM and ER serves to select calculation methods and software tools, a much more detailed description is necessary.

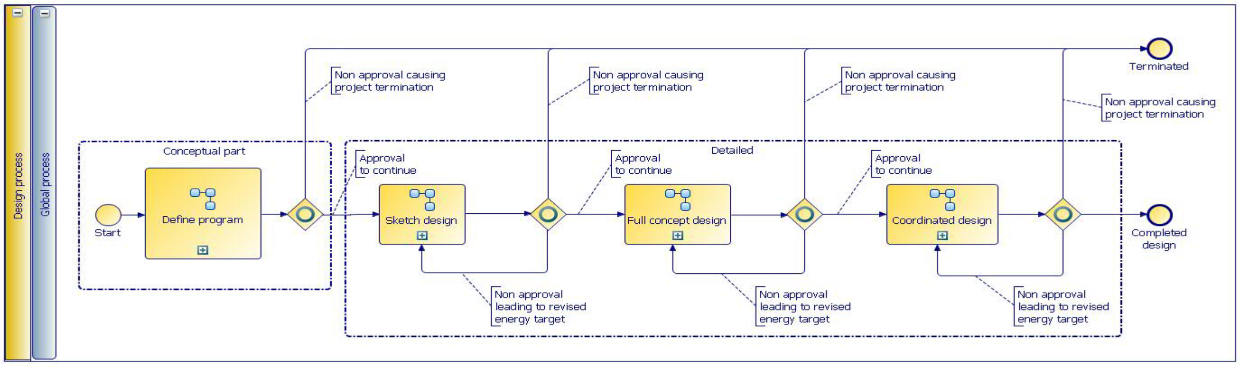

Figure 2: Global design process of a Net Zero Energy Solar Building

The original maps from buildingSMART describe the design process of more traditional buildings. Mapping the design process of a NZESB and comparing it to the design process of buildings with less ambitious energy performance targets indicates a substantial change of tasks, actors as well as required information. The “Net Zero” target strongly influences the entire design process. To meet the energy target, a tight interaction between various disciplines is needed already from the very early stages of the conceptual design. Mapping this interaction provides a clear view on the design process to the extent that future design teams could use it as a manual and as a base for the definition of an integrated commissioning process to achieve the designed performance during the operation of the building. The first maps have been established for dwellings in the Flemish context [24]. As discussed in the next section, the process maps are carefully examined in the context of each of the case studies. Furthermore, a list of requirements and priority targets will be developed for each part of the map for NZESBs.

7 Objectives and Process of NZESB Case Studies

As mentioned above, STB is performing six in-depth case studies of NZESBs from around the world. They are well-diversified by geography and building type and include: 1) EcoTerra House (residential, Eastman (near Montreal), Canada); 2) EnerPos (institutional, Saint-Pierre, Reunion Island, France); 3) Green Tomorrow (residential, Dongbaek, Korea); 4) Leaf House (residential, Angeli di Rosara, Italy); 5) Mondo Solar 2002, residential, Berlaar, Belgium; 6) NREL Research Support Facilities (RSF) (institutional, Golden, USA). This diversity of case studies will allow the unique challenges for achieving NZESB status for different climates and different building types to be identified.

The first goal of the case studies is to thoroughly document the design process and notable features of each building. We will identify how design tools were used in different design stages and for different building systems. The analysis will identify gaps of existing tools and allow the Task to advise tool developers on incorporating features that will facilitate NZESB design. To date, work on the case studies has shown that between three and eight tools are typically used in the design, some created specifically to model a particular feature of the building missing from existing tools or modelled at an insufficient level of detail. Thus, two major categories of potential improvement to NZESB design tools are: improving interoperability between tools so that their unique features can be used to complement each other and increasing the availability of models to assess various technologies.

The second objective of the case studies is to create a calibrated energy model of the subject buildings with one or more design tools. All the selected buildings have monitored performance and weather data, which can be directly compared to the models to ensure accuracy. Afterwards, the buildings will undergo re-design and/or optimization studies, for which the researchers will attempt to achieve net-zero energy for a lower cost, lower end use energy consumption, and/or greater thermal comfort. Preliminary results from the EcoTerra House (the Canadian case study) suggest that merely improving controls and operations can reduce energy consumption by 10-20%. These studies will help inform designers of new NZESBs on the optimal paths to achieve net-zero energy. The results of these case studies will be disseminated in two ways. First, four of them are being presented at the EuroSun 2010 conference [19-22] and one of them is being planned for the ASHRAE 2011 summer meeting. A Sourcebook containing all major STB work will be also be published.

8 Conclusion

The work of SubTask B of the IEA SHC Task 40/ECBCS Annex 52 is focused on design and modelling issues associated with NZESB. As presented in this article, a number of gaps in NZESB design tools have been identified trough a survey, a qualitative benchmark and the beginning of several case studies and design process analysis. Work will continue on the case studies, design process, and quantitative benchmark, which will lead to additional findings and solutions that will assist builders, engineers and architects in the design of NZESB. This information will be disseminated through several conference papers, journal articles, STB reports, and a Sourcebook.

References

[1] Torcellini, P., et al., Zero Energy Buildings: A Critical Look at the Definition. ACEEE Summer Study, Pacific Grove, California, 2006.

[2] IEA SHC Task 40 - ECBCS Annex 52. Towards Net Zero Energy Solar Buildings. 2010 [cited 2010 Jan 31, 2010]; Available from: http://www.iea-shc.org/task40/.

[3] PHPP. PHPP: Passive House Planning Package. 2010 [cited 2010 Jan 25, 2009]; Available from: http://www.passivhaustagung.de/Passive_House_E/PHPP.html.

[4] Crawley, D.B., et al., Contrasting the capabilities of building energy performance simulation programs. Building and Environment, 2008. 43(4): p. 661-673.

[5] Attia, S., L. Beltrán, et al. (2009). “Architect Friendly”: A comparison of ten different building performance simulation tools. 11th International IPBSA Conference, Glasgow, Scotland.

[7] Athienitis, A. (2008). Design of Advanced Solar Homes Aimed at Net-zero Annual Energy Consumption in Canada ISES-AP - 3rd Int. Conference – Asia Pacific Region, Sidney, Australia, Nov. 25-28, 2008.

[8] Hayter, S. J., P. A. Torcellini, et al. (2001). The energy design process for designing and constructing high-performance buildings. CLIMA 2000. Naples, Italy.

[9] Anderson, R., C. Christensen, et al. (2004). Analysis of System Strategies Targeting Near-Term Building America Energy-Performance Goals for New Single-Family Homes, Citeseer.

[10] Shaviv, E. (1999). "Integrating energy consciousness in the design process." Automation in Construction 8(4): 463-472.

[11] Athienitis A.K., Sullivan H.F. and Hollands K.G.T., 1986, "Analytical Model, Sensitivity Analysis and Algorithm for Temperature Swings in Direct Gain Rooms", Solar Energy, Vol. 36, No. 4, pp. 303 312.

[12] Athienitis A.K., Stylianou M. and Shou J., 1990, "A Methodology for Building Thermal Dynamics Studies and Control Applications", ASHRAE Transactions, Vol. 96, Part 2, pp. 839-848.

[13] RETScreen International Renewable Energy Project Analysis Software, Natural Resources Canada, URL: http://www.retscreen.net/ang/d_o_view.php .

[14] Feist, W.; Pfluger, R.; Kaufmann, B.; Schnieders, J.; Kah, O. PHPP 2004, Passive House Planning Package 2004/2007, Passive House Institute Darmstadt, 2004/2007.

[15] Athienitis A.K., Liu C., Hawes D., Banu D. and Feldman D., 1997, "Investigation of the Thermal Performance of a Passive Solar Test-room with Wall Latent Heat Storage", Building and Environment, Vol. 32, No. 5, pp. 405-410.

[16] TRaNsient SYstems Simulation program (TRNSYS), 2006, Version 16, Solar Energy Laboratory, University of Wisconsin, Madison, U.S., May 2010.

[17] Attia, S., et al. A comparative study of the ‘architect-friendliness ‘of simulation tools, in SB 2010. Maastricht, The Netherlands.

[18] Norwegian buildingSMART chapter, http://www.buildingsmart.no

[19] Bucking, S., A. K. Athienitis, et al. (2010). Design Optimization methodology for a near net zero energy demonstration home. EuroSun 2010, Graz, Austria.

[20] O'Brien, W., A. K. Athienitis, et al. (2010). Applying a design methodology for a net-zero energy house to evaluate design processes and tools. EuroSun 2010, Graz, Austria.

[21] Cellura, M., L. Campanella, et al. (2010). The evaluation of energy performances of a net zero energy building: an Italian case study. EuroSun 2010. Graz, Austria.

[22] Klein, R., Claes, K.,et al. (2010). A Belgian pilot project for zero energy office buildings. EuroSun 2010, Graz, Austria.

[23] L. Pagliano, P. Zangheri, Comfort models and cooling of buildings in the Mediterranean zone, Advances in Building Energy Research, vol 4, 2010, pgg 167-200.

[24] Biesbroeck, K., Klein, R.,et al. (2010). Design processes for Net-Zero Energy Buildings. Reinventing the design process: How to improve information exchange and software tools, in SB 2010. Maastricht, The Netherlands.